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The False Promise of Desert Agriculture

RUSSELL CLEMINGS

CHAPTER TEN

Science Searches for Answers

FOR THE DESERT FARMING empires that now account for one-third of the world's agricultural production, there are two alternative futures. One version is bleak: farmers keep using big floods of water to flush salts from their fields, as most do now, but in time run out of places to dump the saline effluent. Salt and water then build up underground until crops are either drowned or poisoned, and today's desert bloom quickly withers. The other future is brighter: farmers learn to irrigate gingerly, using only enough water to keep the soil's salinity tolerable. Perhaps they capture the resulting trickle of saline drainage and reduce its volume further by reusing it to irrigate salt-tolerant crops. Then they dispose of what's left, concentrated by then into a much more easily managed fraction of the drainage they were producing before, thus keeping salinity problems at bay for decades, if not centuries.

Which of these paths the future of desert farming will follow is still uncertain. But if the future turns out to be bright, then historians may find significance in what happened in a cluster of Moorish-style buildings at the foot of Mount Rubidoux in Riverside, California, in the late 1960s and early 1970s. There, in a cerebral ferment that seems out of place in the humdrum world of irrigation, a small group of soil and plant scientists and engineers

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in the Department of Agriculture's U.S. Salinity Laboratory came up with a new vision of the future. First they studied the interplay of plants, soils, salt, and water and evaluated new technologies such as drip irrigation. Then they showed how farmers could save water and ease their drainage problems by striking a balance between using too much water—the traditional approach to desert agriculture—and using too little. Their techniques have the potential to revolutionize the way we grow food in arid lands. They could enable farmers to grow more and better food with less water and fewer chemicals, while spending less money and creating far smaller amounts of environmentally damaging drainage. But before that can happen, science will also have to overcome the fears of tradition-bound desert farmers—fears based on some lingering superstitions about salt.

"Salt balance" is a time-honored precept of irrigation that says, in essence, that what goes in must eventually come out: all of the dissolved salts that farmers unavoidably put on fields when they irrigate—salts that hitchhike in even the purest water supplies—must be carried away sooner or later in drainage water. For most of the twentieth century, the notion that long-term irrigation is impossible without salt balance has been an article of faith in desert agriculture. In the name of salt balance, entire rivers like the San Joaquin, the Colorado, and the Rio Grande have been polluted with the saline drainage of desert farms. Generations of farmers were afraid that if they didn't use plenty of excess water to rinse away all the salts they were importing, then their fields would be poisoned by the buildup. There was only one problem with salt balance: it was utterly unnecessary.

For most of its half century of existence, the U.S. Salinity Laboratory, housed on a parklike campus on a back street in a 1920s Riverside neighborhood, has stood in the front row of the salt balance choir. In 1954, the laboratory digested the results of its first decade and a half of research and produced a definitive text on managing irrigation in arid regions, titled "Diagnosis and Improvement of Saline and Alkali Soils" and known in USDA shorthand as Handbook 60, in which salt balance was the one true gospel. In Handbook 60, a dozen of the lab's most senior and credentialed scientists—including Charles Bower, a leading authority on soil chemistry, and Leon Bernstein, the world's foremost expert on the salt tolerance of plants—held forth on matters of soil, salt, water, plants, and all of their interactions. The book's centerpiece was its discussion of the leaching fraction, which it defined as the portion of the irrigation water that must be trickled through the root zone to keep soil salinity from rising above a given level. Handbook 60 boiled down the many complexities of the leaching fraction to a simple yet elegant formula—the ratio of the salinity of the irrigation water to the maximum salinity that could be tolerated by the crop without a yield loss. Reduce leaching fractions to less than that, the handbook said, and salt balance would be lost. The effects might not be noticeable at first, but over time crop yields would decline and the soil would be rendered unproductive.

Handbook 60 became an instant classic. Its formulas and classification schemes were transplanted directly into agronomy textbooks; to this day, agriculture students sit in lecture halls and listen to their professors recite its terse, cadenced prose, only slightly altered to disguise its true authorship. Among its virtues was its brevity. In only 160 pages, Handbook 60 reduced the complexities of soil and water chemistry in arid regions to a mere handful of fundamental principles and algebraic equations. In the world of Handbook 60, there were three types of saline or alkali soils: those with salt, those with sodium, and those with both. There were two factors affecting the usability of water—the salt content and the proportion of sodium to other cations—and four classifications for each, from low hazard to very high hazard. Seven principles guided management of arid-region soils for salinity and alkalinity; five categories spoke to the salt tolerance of plants.

So simple and sturdy was Handbook 60 that it was widely regarded as the final word on the subject of salinity, and for a while the salinity laboratory's work appeared to have reached its logical conclusion. "I can remember Bob Ayers, who was the extension man for salinity at the University of California in Davis, telling me that at that time he thought that salinity issues were just about dead, that there was nothing new coming out of salinity," said Glenn Hoffman, an engineer who worked at the salinity laboratory as a water management specialist from 1966 to 1984. Some knew better, including scientists whose work formed the foundation for Handbook 60. "What Handbook 60 did, for one thing, was identify some knowledge gaps that needed to be filled by new fundamental research," said Steve Rawlins, a soil physicist who joined the lab in 1964. "During the lab's initial couple of decades, prior to the publication of Handbook 60, there was a lot of argument and a lot of interaction and some real effort to integrate concepts of salinity into principles that could be applied. Then, after Handbook 60, I think that was lost a little bit. There was a frustration that they couldn't go any further because they didn't have some fundamental response functions" for things like the salt tolerance of plants and their reaction to being irrigated with waters of varying salinity in varying soil types. "There was a period of backfilling there, in the late 1950s and early 1960s, filling some of the holes that had been identified with Handbook 60," Rawlins said.

During that period, Bower, Bernstein, and the lab's other scientists went back to the lab bench. Bernstein ran hundreds of tests to determine salt-tolerance curves for all types of crops, from strawberries and beans to cotton, corn, and alfalfa. Other scientists studied the details of soil chemistry—the interplay of ions of such elements as sodium, calcium, and magnesium in solutions of soil and water. Still others looked at physical questions: How does water move through the soil after irrigation? How much of it fills the pores of the root zone and how much migrates downward past the roots to the water table? As the 1960s progressed, the older scientists were joined by younger ones eager to make names for themselves—bright, ambitious men with fresh doctorates from some of the nation's best agricultural schools: California, Purdue, North Carolina State. Rawlins arrived in 1964 with a degree in soil physics from Washington State and four years of experience at an agricultural experiment station in Connecticut. Jim Rhoades, a chemist, came the following summer, while he was finishing his doctorate at the University of California at Riverside. Another physicist, Jim Oster, came that same year with a doctorate from Purdue. Hoffman, from North Carolina State, arrived in the fall of 1966.

Of all the lab's projects during that time, Bernstein's plant work appeared to be making the most progress. Bernstein's basic mission was to reexamine the theoretical underpinnings of the most important Handbook 60 concept, the leaching fraction. It was no secret in arid regions that some kind of leaching fraction was necessary; without the cleansing rains that are typical of humid climates, the only way to flush excess salt from the soil was to apply extra water. But Handbook 60's simple formula for calculating the leaching fraction was based on experiments that Bernstein regarded as suspect. The problem lay in the way the experiments had been designed. To gauge the tolerance of plants to saline water around their roots, previous researchers had given their plants lots of water, enough to ensure that there would be no change in the salinity of water from the soil surface to the very bottom of the root zone. Each root would then be exposed to "soil-pore water" of the same salinity, no matter whether it lay near the soil surface or far below it. This approach made experiments simple to design and easy to reproduce, but it required heavy, steady irrigation, enough to maintain a constant downward flux of water through several inches or even feet of soil.

With help from agronomist Lee Francois, Bernstein tried to determine how plants would respond if their water rations were cut to less than what was needed to keep soil salinities constant. Working in a greenhouse, he used a series of devices called lysimeters

to carefully control and monitor how much water each of his alfalfa test plants was given. The lysimeters—concrete pipes sixty inches long and twenty-four inches in diameter, standing on end—each held a single plant or a cluster of plants. They had collectors at the bottom for drainage water and sampling points every twelve inches along their walls, so that soil water salinities could be tested at various points in the root zone. The scientists fine-tuned their water applications until they were running a different, carefully calibrated leaching fraction in each lysimeter. In one group of lysimeters, leaching fractions were 25 percent, roughly what farmers outside the lab were using. Other lysimeters had lower leaching fractions—12.5 percent in one group, 6.2 percent in another, and 3.1 percent in a third.

According to the thinking that prevailed when Handbook 60 was written, the plants irrigated with the lower leaching fractions should have been sickly. But very quickly Bernstein found that he could cut the leaching fraction dramatically without seeing any yield reduction at all, especially with waters of low salinity. At the same time, some interesting things happened to the salinity of the soil-pore water as the leaching fraction was reduced. Instead of there being a constant level of salinity from the top to the bottom of the root zone, a gradient developed with less saline water at the top and higher salinity at the bottom. Moreover, Bernstein's plants adjusted to the salinity changes by altering how they took water from the soil. Instead of taking relatively equal amounts of water from each depth in the root zone, the plants began to show a preference for the low-salinity water at the top. Their roots absorbed large amounts of water in the first few inches of the soil and progressively less in the lower, saltier regions. In effect, as the water trickled downward, the plants concentrated the water and its salts into a smaller and smaller volume. This finding was tremendously significant. Whereas plants watered in the traditional way unleashed great floods of water at the bottoms of their root zones, Bernstein's stingily watered plants released similar amounts of salt

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in much smaller volumes of water. The plants, in essence, were wringing all of the utility they could from the irrigation water before letting it go. And then, instead of a torrent of hard-to-manage drainage, they released a tiny trickle.

While Bernstein studied his lysimeters, over in soil chemistry, Bower and his young assistant, Jim Rhoades, were coming up with similarly provocative results. Bernstein's findings, for all their importance, did not represent a direct indictment of salt balance. For the most part, the conventional wisdom remained intact: every molecule of salt that came in with the irrigation water would have to leave with the drainage, albeit in more concentrated form. But the soil chemistry group was onto something altogether different. Setting up their own rows of lysimeters, Rhoades and three collaborators sowed alfalfa and irrigated it with waters of eight different salt and mineral compositions, chosen to represent a cross section of irrigation waters from the western United States. For each type of water, they set up three experiments, one using a high leaching fraction, one moderate, and one low. In all, there were twenty-four experiments.

They found, as Bernstein did, that there was no obvious yield reduction at the lower leaching fractions. But they also did calculations to determine how much salt was entering the lysimeters with each irrigation and leaving in the resulting drainage, and they found, oddly enough, that less salt was leaving than had entered. Rhoades and the others surmised that some of the salts—mainly calcium-based salts—were precipitating in the subsoil as carbonate and gypsum minerals. These minerals were largely innocuous; unlike the more dangerous sodium ions, which can bind tightly with clay particles and turn soil into a tightly packed powder that repels water, the calcium and magnesium ions were harmless unless dissolved in water. And reducing leaching fractions had another beneficial effect—it slowed the natural "weathering" or breakdown of soil particles into simpler particles, many of which

were salts. The implication of those two findings was simple: salt balance wasn't just unnecessary, it was harmful because it wasted water and led farmers to flush benign salts out of the soil, where they weren't hurting anything, and into the nearest river, where they could cause all kinds of problems.

While all of this was going on, the soil physics group led by Rawlins was focusing on the mechanics of irrigation—trying to find a way to moisten a patch of soil as uniformly as possible and with as little wasted water as possible. Traditional irrigation systems, little changed since their development in ancient Egypt and Sumeria, relied on gravity to move water around and get it into the soil. Rawlins was convinced that modern irrigation systems, such as sprinklers or drip irrigation, could be far more efficient. The new systems had one thing in common: they were pressurized. Instead of conveying water across the field by gravity, they used pipelines, which meant that farmers no longer needed to put extra water on the near ends of their fields to make sure enough water reached the far ends. Nor did they need to continue to apply their water all at once; instead, they could apply it slowly (or, in the case of drip irrigation, continuously), filling the soil gradually and stopping before water began trickling past the bottom of the root zone. Using pressurized systems, in short, allowed farmers to simulate in the field the conditions Bernstein created in the lab with his lysimeters—a gradient of steadily increasing salinity from the top to the bottom of the root zone.

Each cluster of scientists at the salinity lab during that time was discovering things that defied the conventional wisdom about how to irrigate a desert soil. Bernstein was demonstrating that crops would tolerate higher salinity than had been supposed; Bower and Rhoades were showing that some salts could be parked in the soil indefinitely, instead of being drained away; and Rawlins's group was proving that pressurized irrigation systems could drastically

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reduce wasted water. But for a long time these tantalizing pieces remained just that, pieces, and no one knew what the puzzle was supposed to look like.

One reason was the lab's peculiar culture. Under Bower, who was the lab's director throughout the 1960s, the freewheeling debates that had accompanied the development of Handbook 60 were set aside in the interest of producing publishable research. Partly, Rawlins said, this shift was attributable to Bower's personality: "His concept of doing research was, 'You run some experiments, you get some data points, you draw a line through them and you publish it.'" But Bower also seemed threatened by the younger scientists and their powerful egos. He clashed with Rawlins over an expense voucher and held the grudge for months; he fell out with another young scientist—a man who had been his protégé—when he learned that the younger man was talking to recruiters from a university agriculture department. And he grew weary of mediating intramural fights among the young scientists. Rhoades and Rawlins were barely speaking; though the disagreements were mostly scientific—Rhoades liked to base his work strictly on the results of his experiments, while Rawlins preferred to formulate sweeping theories that could be applied more widely—they were nonetheless intense. Even the more mild-mannered scientists, like Hoffman and Oster, saw themselves as rivals for funding and recognition. Bower did little to soothe these matters and retired in 1971, soon after he became eligible.

It took more than a year for the Department of Agriculture to name his replacement, and when the selection was finally made, the choice was a surprise: Jan van Schilfgaarde, a respected drainage engineer and assistant director of the soil and water division of the department's Agricultural Research Service. Until then, van Schilfgaarde had been Bower's boss, overseeing the salinity lab and several other ARS stations. But in Washington he had just led an unsuccessful middle-management revolt against a proposed agency reorganization plan, and in retaliation had been demoted

and sent to Riverside, "because that was small enough that I couldn't do any damage."

His career up to that point had been exemplary. Born in the Netherlands, he came to the United States in the late 1940s and got three agricultural engineering degrees—bachelor's, master's, doctorate—from Iowa State University. He moved to North Carolina State University as a professor of agricultural engineering, then joined ARS in 1962. "He was in research for only about ten years, but he was editor of the Agronomy Society's monograph on drainage, which is a world's authority book," Hoffman said. "He had already gained the respect of everybody in the world in terms of his drainage authority." In Washington, his job had been to do the agency's dirty work; when there was a need to fire someone, he broke the news. From that experience, he learned to be simultaneously diplomatic and firm. He was also eloquent in a way that seems to come only to those who have mastered English as a second language. He had a rare ability to understand and synthesize raw research results and to sense the common threads that could be melded into new practical knowledge. And having been bounced out of the nation's agricultural research hierarchy in midcareer, he had something to prove.

Van Schilfgaarde was already familiar with the puzzle pieces of the salinity lab's recent work because he had supervised it from one step removed, but he could afford to take a broader view than the scientists themselves. Bernstein thought that his plant work opened the door to using saline waters for irrigation, and it did; Rawlins believed that his studies of irrigation technology would permit farmers to stretch scarce water supplies, and they did; Rhoades felt his soil chemistry research would help reduce salt loading into rivers like the Colorado, and it did. But until van Schilfgaarde's arrival, no one had assembled all of the pieces, and mutual animosity was getting in the way.

Van Schilfgaarde quickly sized up the situation: "They thought they were competitors, especially for money." He immediately en-

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listed Rhoades, Rawlins, and Bernstein to help him write a paper that would meld the lab's findings into a new ethic of water conservation for desert farmers. He also looked for money to set up demonstrations, figuring that an influx of cash would force the scientists to settle their differences. "I think most of the ideas were already there, and I don't think Jan did the integration himself; I think it was shared," Rawlins said. "But what he did do was he built a team. That's a good way to build a team—throw down a chunk of money and say, 'In order to have some of this money, you've got to work together.'"

"One thing that's unique about Jan," Oster said, "is that he can stir people up and lead them without causing internal frictions that aren't resolvable. . . . He didn't bang heads. It was question-and-answer time. It was sitting down and writing a paper." Without van Schilfgaarde's leadership, Oster said, "We would never have struck out to combine that research into a minimized leaching concept. Hoffman wasn't inclined at that stage of the game. Jim Rhoades has since developed that sort of leadership ability, but back then he was still stuck at the lysimeter stage. It was just a matter of good timing, and Jan being the kind of leader who could bring it about."

Van Schilfgaarde brought his diplomatic skills to bear outside the lab as well. At a meeting of soil scientists, Rhoades and Oster ran into Ron Reeve, a former salinity lab scientist who had moved into the ARS hierarchy and had just been appointed to a committee that was studying ways to reduce the Colorado River's salinity. President Nixon had promised Mexican President Luis Echeverria that the United States would try to resolve Mexico's longstanding grievance over the high salt levels that the river carried when it reached Mexico's diversion point at Yuma. The front-running solution was the giant desalination plant the Bureau of Reclamation wanted to build at the river's edge just north of the Mexican diversion. "Jim and I came back from that meeting," Oster said, "and mentioned to Jan that as far as we could tell nobody was going in there and

talking about farm water management improvements" as a way of reducing the river's salinity. "Well, it didn't take Jan very long at all to get started on that one."

A few weeks later, van Schilfgaarde was called to meet Herbert Brownell, whom President Nixon had appointed to negotiate a settlement to the salinity problem. Van Schilfgaarde recalled:

> He said, "We have a proposal from Interior to solve the problem by having the federal government pay for it and build a desalting plant. My contacts at the Office of Management and Budget tell me that's not a good proposal. I want you to get me a counterproposal, based on agricultural insights, and I'd like to have it before you leave town." This was on a Wednesday. And I told him that he was crazy, that I wasn't about to do that. That first of all, I didn't even know where Wellton-Mohawk was. I hadn't been in the West long enough to know. I had to get out a map to find out where it was, and he thought that I, by myself, was going to write a counterproposal to an agency that spent five years learning about it?
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> So he said, "Well, I have a car standing by. I'll send you over to OMB, and there are some EPA people over there. You can find out what kind of work they've done, and I would very much like to have your insights by Friday night." Well, I finally dickered myself into Tuesday night, which still wasn't very much time. I called the lab and told the guys more or less verbatim what I'd been told, because I didn't know enough to give them any instructions. I said, "Cancel anything you're planning this weekend. We're going to be working Saturday and Sunday to see what we can do." And that's what we did; we developed a counterproposal.

Van Schilfgaarde, Rawlins, Rhoades, Oster, and Hoffman spent the weekend around a table punching numbers into desktop calculators and writing them on chalkboards, referring to wall maps and stacks of reports from other agencies. "We had access to some worthwhile reports," van Schilfgaarde said. "The Bureau of Reclamation had gone to the Agriculture Department earlier and asked for advice when the drainage problem first started in the early 1960s. So in the files there were a number of reports that gave us areas and numbers and drainage volumes and cropping patterns."

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From these data, the scientists produced a short memo that outlined how improving irrigation efficiencies in the Wellton-Mohawk Valley could accomplish the same things as a desalting plant. From 220,000 acre-feet of drainage that Wellton-Mohawk farmers produced each year, desalting would have generated some 45,000 acre-feet of salty brine, which would have been dumped into the Colorado delta below Mexico's diversion. The remaining 175,000 acre-feet, its salinity now acceptable to Mexico, would have gone into the river. Implementing the salinity laboratory's plan, farmers would have improved their efficiency by enough to reduce their diversions from the Colorado by 181,000 acre-feet per year. That water would have stayed in the river for Mexico's use, while the valley's remaining drainage, totaling only 39,000 acre-feet—essentially the same amount as the desalting plant's briny reject stream—would have been dumped into the Colorado delta just like the desalting plant's brine. "We projected into the future and showed that you could achieve essentially the same thing by management as you could by desalting," Rawlins said.

Van Schilfgaarde said Brownell was struck by the fact that the salinity laboratory's proposal would save almost the same amount of fresh water as the desalting plant at a much lower price. At the next meeting of his task force, when OMB delegates made a strong pitch for the salinity lab's plan, Brownell directed that improving the valley's irrigation efficiency be studied further, although his principal remedy remained a desalting plant. In an interview in 1989, Brownell said he was reluctant to embrace the lab's plan because it was unproven, but van Schilfgaarde said Brownell gave him another explanation:

> He called us back in December and he said, "I have made my decision. My report is handwritten so there can be no leaks, and I will present it in person to President Nixon tomorrow." But he wanted to brief us first, since we had given him input. So he talks for half an hour or so to tell us what he was going to do and why. He ignored my proposal entirely. He called me aside afterward and said, "Technically, you're right, but politically I can't sell it." I said, "Well, you're the ambassador; I'm the engineer. That's your privilege." Obviously I was disappointed, but I had no hard feelings.

Archives from Brownell's assignment make clear that the salinity lab's plan was torpedoed by the seven Colorado River basin states, who wanted to make sure that the full burden of whatever solution was chosen would fall on the federal government. Since the lab plan required Wellton-Mohawk farmers to make wholesale changes in the way they irrigated, it would not have met that requirement, and the basin states stubbornly refused to consider it. Yet the lab's plan clearly appealed to the White House's budget watchers. The OMB protested Brownell's desalting plant recommendation even after it went to Nixon; the president's science advisor and the chairman of his Council on Environmental Quality voiced objections as well. Their joint letter prompted a testy response from the usually diplomatic Brownell: "The memorandum fails to cover the attitude of the basin states . . . [and] without their support one does not have a solution to the problem with Mexico." The OMB used its influence with White House Chief of Staff H. R. Haldeman to keep Brownell's recommendation from reaching Nixon's desk for several months, but in the end the states got their way.

Shortly after Nixon accepted Brownell's proposal, the salinity lab's plan was reborn. Without warning, the Bureau of Reclamation revised its estimate of what the desalting plant would cost from forty-two million dollars, as it had promised Brownell, to sixty-two million dollars, an increase of 48 percent in less than a year. Bureau officials blamed inflation, refinements of sketchy initial plans, and unforeseen factors such as the need to buy some of the desalting plant's power from costly private sources. But Brownell smelled a rat. "That's what happens to all big federal projects," he said. "Everybody underestimates the costs to get the thing started, then after it's started they figure they can be more realistic and get additional money so the original money won't be wasted," he said. "It's the bureaucratic attitude." Equally annoyed was Nix-

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on's national security adviser, Henry Kissinger, who had been an early supporter of the desalting plant, which he saw as a painless solution to a nagging diplomatic problem with Mexico. "It just irritated the holy hell out of him that he had obviously been snookered," van Schilfgaarde said. "That's the way he looked at it. His letter didn't say that, but the tone was harsh and it's pretty obvious that he was pissed off as hell. And that was our entrée."

Concern over the desalting plant's escalating costs gave a boost to plans for an interagency task force that would look into the salinity lab's ideas for Wellton-Mohawk. Brownell had proposed the panel almost as an afterthought to the desalting plant, a hedge against what he saw as the remote chance that the plant's reverse-osmosis desalting technology might not work. After Kissinger's outburst, the committee suddenly had attention from the upper levels of the White House. As long as the seven basin states controlled fourteen Senate votes, including key committee assignments overseeing the Department of the Interior, the Bureau of Reclamation, and their appropriations, prospects for doing away with the desalting plant altogether remained dim. But if the task force could provide evidence that the salinity lab's methods would accomplish the same ends, then there would be at least a slim chance.

The task force was based in Washington and consisted of agency heads and other policymakers; van Schilfgaarde was appointed to a field-level technical committee that did much of the nuts-and-bolts work. By then, the minimized leaching concept was further along than it had been during that rushed weekend meeting. The lab had finished its minimized leaching paper and was working with another Department of Agriculture agency, the Soil Conservation Service, to test the minimized leaching concept in a cornfield near Grand Junction, Colorado, where over-irrigation was pushing salt out of the naturally saline soil and into the Colorado. In addition, because he was no longer operating under Brownell's

rushed deadlines, van Schilfgaarde was able to build a convincing case in the committee meetings for what his scientists were proposing. Still, the desalting plant's backers in the Bureau of Reclamation clung tenaciously to their cherished blueprints.

"The Bureau of Reclamation from the beginning thought this on-farm program was foolish," van Schilfgaarde said. "It was like pulling teeth all the way through. The bureau started out with the idea that this was not possible, that obviously Wellton-Mohawk was one of the best irrigation districts in the world and therefore we couldn't possibly improve its efficiency." But van Schilfgaarde had the bureau outnumbered. He had formed an alliance with another Department of Agriculture official and with the committee's two Environmental Protection Agency delegates, whereas the bureau had only three representatives. He also worked on the consciences of the bureau officials, appealing to their sense of engineering ethics, which they like him had acquired through years of rigorous technical training:

> We insiste[illegible]od water measurement. At one stage, we had a meeting. It got a [illegible] raucous; we were arguing about whether the district's water meas[illegible]ments were any good. A couple of the bureau engineers insisted they were just excellent. We said we didn't think so, but I didn't have any real basis for that except hearsay. So we decided to call the water master and get in the car and go out to Wellton-Mohawk and have him show us how they measured. When we got there, the *zanjero* [ditch tender] opened a gate, then went to his pickup and got out his impellor water meter, which is a perfectly good piece of equipment if things are going right but doesn't work worth a damn if there's air coming out of the pipe with the water, and this thing was bubbling air like mad. The meter has a needle on top that goes around, and he used a wristwatch to time it, which was not very accurate. And the needle was broken off, but you could see there was a scratch on the shaft, so he was just watching the scratch go around. Then he looked at a table and converted his measurements from one-decimal-place accuracy to three-place accuracy by interpolating, essentially. Those of us who were engineers were just standing around saying, "My God.

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> Jesus." Then—and this was the clincher—he took the meter out and tossed it into the bed of the pickup from about ten feet away, and it landed on the bearing. Nobody said anything. We'd made our point.

In the end, van Schilfgaarde said, the bureau people were ready to concede that the salinity lab's plan could work—that the Wellton-Mohawk farmers were using so much water that a simple conservation effort incorporating minimized leaching would be likely to reduce drainage flows by enough to eliminate the need for a desalting plant. But the engineers were unable to get their superiors to sign off on the idea, so a curious compromise was struck. "We proposed to do both," van Schilfgaarde said, "to put in the on-farm improvements, and at the same time to build the desalting plant. It was a lousy compromise in a technical and financial sense, but politically it was interesting." The panel concluded that it would be cheaper to improve the efficiency of the Wellton-Mohawk farmers than to operate the desalting plant, let alone build it, so even if the plant were constructed, the government could still abandon it, continue to implement the on-farm improvements, and justify the decision under a cost-benefit analysis. Van Schilfgaarde said this odd compromise was proposed by a bureau engineer, John Maletic, the agency's water quality office chief. "Even though he was a dyed-in-the-wool bureau man, he really saw things our way," van Schilfgaarde said. "It was an obvious nonsense statement, but by writing it that way he was able to get everybody to sign off on it so we could go ahead with the on-farm program."

A few months later, in 1974, the EPA came through with a grant for the salinity lab to do some demonstration projects in Wellton-Mohawk. The scientists holed up in a motel in Tacna, a dusty truck-stop crossroads at the center of the long valley. Said Hoffman, who led the field teams:

> The scientists went down [from Riverside] with the technicians for weeks at a time to put the experiments in. There was one motel. We

> would go down on a Sunday afternoon. We would arrive late, and the motel operator would leave the back door unlocked for us. There was a big feedlot there at the time, and there were truckers hauling manure out of the feedlot, so some of our rooms smelled kind of ripe, depending on who was staying there the previous week. We probably made them smell worse after a day or two.

There were two principal growing regions in the Wellton-Mohawk Valley. Along the south edge, just north of the present route of Interstate 8, was a high, sandy mesa dotted with ten thousand acres of citrus groves. Growers in that area had fallen into the habit of giving their trees at least twice as much water as they needed. They built low dikes about every sixth row of trees and flooded the resulting basins. "There was a little bit of a slope, and the soil was very sandy." Hoffman said, "so they would have to apply ten inches in order to get the water six inches deep over the entire area." Even to the casual observer, the results were obvious. "There was water running out of the slope of that mesa, eight feet above the valley floor," recalled one Wellton-Mohawk farmer, Bob Woodhouse. Below, on the low ground Woodhouse farmed, the over-irrigation was less extreme but still notable: farmers there were giving their crops, primarily alfalfa, cotton, and melons, about one-third more water than they needed.

The scientists set up separate experiments for each area. On the sandy mesa, they installed drip irrigation in a mature grove of Valencia oranges to precisely control the amount of water that went to each tree. After calculating how much water an average tree required for evapotranspiration the scientists then applied that amount plus one of three small leaching fractions. "We put on what we thought was ET plus 5 percent, plus 10 percent, and plus 20 percent, to see how much water was really needed over the long term," Hoffman said. "And what we found was, it took five years before even the 5 percent leaching was not sufficient."

Down on the valley floor, a similar experiment was conducted. The scientists divided a twenty-acre alfalfa field into two portions.

On one, measuring five acres, they installed what they called a "traveling trickler," a giant device similar to the center-pivot sprinkler rigs that farmers on the Texas high plains use, only fitted with drippers instead of sprinklers. On the other, they created a "dead-level" system with a big gate in one corner to let the water in and a perfectly leveled field that allowed it to spread quickly. "The idea was to apply the water in a large volume, very quickly," Hoffman said, "so you could put the same amount of water on all parts of the field. We would put on fifteen cubic feet per second of water, and in less than an hour we'd have six inches of water across fifteen acres."

The twin experiments established beyond any doubt that leaching fractions in the valley—and the drainage volumes that resulted—could be cut sharply without affecting crop yields. Soon, the Soil Conservation Service was offering cost-sharing grants to farmers on 23,800 of the valley's 65,000 acres for irrigation efficiency improvements modeled on the salinity lab's methods. "We demonstrated that we could make progress," van Schilfgaarde said. "But in the process, we ran into one problem after another when the bureau realized that we were trying to crack down on the size of the desalting plant." The technical committee was still convened, and van Schilfgaarde and Rawlins attended the increasingly tense meetings. Rawlins said:

> Boy, those were some rough meetings, let me tell you. The people who were there from the bureau were just like a military organization. They had this technology that they were going to use come hell or high water. Even their own economist pointed out that there were better ways of doing it. In fact, he pointed out that the cost of the desalting plant, just to run it, was equal to the entire gross product of the Wellton-Mohawk Valley.

Meanwhile, the plant's costs continued to escalate, fueled by rampant late-1970s inflation on top of the usual bureaucratic revisions. While the bureau busied itself building a small pilot

desalting plant just upstream of Yuma, costs for the full-sized plant ballooned from the forty-two million dollars that Brownell was promised in 1973 to a July 1977 estimate of $ [illegible] illion—an increase of more than 300 percent. Inflation accounted for only one-third of the increase. The plant's estimated completion date also slipped: Brownell had predicted the plant would be ready by 1978, but when that date arrived, the bureau was saying that completion was still four years away. In the technical committee meetings, van Schilfgaarde goaded the bureau engineers into re-evaluating the need for the desalting plant in light of the early results from the on-farm program. As he expected, the results showed that extending the effort to the entire Wellton-Mohawk Valley would eliminate the need for the plant altogether. The committee produced a report, and in early 1979, when the bureau went to Congress to ask for still more funds for the desalting plant, the salinity lab's scientists decided to intervene.

Rawlins made an appointment with one of his neighbors, George Brown, who happened to be a member of Congress and sat on the House Interior Committee:

> In my unofficial capacity as a citizen and a taxpayer, my wife and I sat down with George Brown one day in his office and told him what was going on. And he said, "I don't like it any better than you do. I'll take this up and deal with it, and if it turns out that it's something we can win, I'll take full credit for it. If it's not, you won't hear anything about it." Of course, as a government employee I certainly didn't want my name used.

It was a high-risk strategy, but it won tacit approval from van Schilfgaarde. "It was strictly against the rules," he said. "I felt that I couldn't afford to get caught, but if he [Rawlins] wanted to, then what the hell." After the meeting, Brown began a sustained—and in the end, partially successful—attack on the desalting plant, with salinity lab scientists steadily shipping him incriminating documents. Van Schilfgaarde said:

> He wrote a letter to the secretary of the Interior asking whether all alternatives had been considered and whether in fact we had to go through with the desalting plant, and the answer he got was that there were no alternatives. [Brown] then returned the letter, with a copy to the White House, saying, "You've just told me that there are no alternatives. Then how come I have in my hand a report from one of your committees that discusses half a dozen alternatives?" In other words, our report. We fed him all the stuff that he needed, but obviously not officially.

Brown bottled up Interior's appropriations request for more than a year. "That put the bureau on notice that they had better pay some attention to the on-farm program and not just give it lip service," van Schilfgaarde said. Although Brown ultimately couldn't kill the desalting plant, he was able to get its capacity downsized from ninety-six to seventy-three million gallons per day and to get the on-farm improvements expanded from 23,800 acres to 38,000 acres. The effort paid dividends: by 1981, the valley's average leaching fraction had dropped from 31 percent to less than 12 percent, and the amount of salty drainage it was dumping into the Colorado had been cut in half. But construction—as well as delays and cost escalation—continued on the desalting plant. When at last it was deemed complete in 1992, the plant had cost $226 million to build, and would cost eleven million to thirty-three million dollars per year to run, depending on how much it was used. Meanwhile, for almost exactly the same results, the federal government had spent less then thirty million dollars to improve the irrigation efficiency of the Wellton-Mohawk Valley's farmers.

As its Wellton-Mohawk project matured, the salinity lab's scientists moved on to other things. Having already demonstrated how farmers could reduce their drainage to insignificant levels by using efficient modern irrigation methods, the scientists—especially Rhoades and Rawlins—turned to a related question: what to do

with the tiny fraction of salty drainage that remained after leaching fractions had been reduced as much as possible.

On the chalkboard, this problem should not have existed. Reducing leaching fractions to their minimum levels and letting crops concentrate the salts in the soil-pore water to their theoretical maximums should have wrung every last bit of utility from the applied water, leaving only unusable saline drainage to come out of the bottom of the root zone. But the reality was not that simple. "Generally, you can't concentrate the drainage enough in one cycle to take all of the crop-producing value out of it," Rawlins said. "You just can't irrigate that uniformly. There's always some water that leaks past. You always had a higher leaching fraction than the theoretical model would predict, and so you always ended up with a bit more drainage water."

So over the next few years, in the late 1970s and early 1980s, former rivals Rhoades and Rawlins joined forces to set up experiments in two of California's most important agricultural valleys—the San Joaquin and the Imperial—and to develop a scheme for reusing drainage water by alternating high-salinity drainage and low-salinity irrigations on successive crops. They began in 1976 in the Lost Hills Water District, located in the remote southwestern corner of the San Joaquin Valley along I-5 northwest of Bakersfield. At that time, the state Department of Water Resources (DWR) and the federal Bureau of Reclamation were launching another in an interminable series of studies of the valley's severe drainage problems; and as usual, their efforts seemed destined to rely on the controversial drain to the Sacramento–San Joaquin delta. Correctly sensing that the studies were being rigged, Rhoades threw down a gauntlet. "I was a voice crying in the wilderness," he said. "No one else was speaking up about the fact that part of the solution could be the reuse of these drainage waters. So I wrote a paper and went to a meeting and presented it. In a way, I did it as a challenge, to say, 'Hey, you guys really ought to be considering this.'" The paper, which Rhoades presented at a meeting of the American Society

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of Civil Engineers, challenged the state water planning agencies to prove him wrong in his basic contention: that moderately saline drainage waters could be used on many different crops so long as fresh water was used at the crop's most sensitive stages, especially germination, and so long as subsequent crops were watered with fresher water so that salinity didn't build up to dangerous levels in the soils over time.

Rhoades's ploy had the desired effect: four agencies—the DWR, the bureau, the Lost Hills Water District, and the Kern County Water Agency, which was the water wholesaler for that region—accepted the challenge and agreed to pay for testing Rhoades's reuse scheme on cotton fields in the Lost Hills area. The plan was to establish seedlings using low-salinity delta water from the California Aqueduct, the region's major canal, followed by higher salinity drainage water during later growth stages. An unexpected complication arose during the experiment's second season: the regional groundwater, which had been rising slowly over time, shot suddenly upward. Practically overnight, the water table rose from fifteen feet below the surface to less than three, and it became difficult to sort out the effects of the saline irrigation water from the effects of the high though somewhat less saline water table. Nonetheless, yields on the drainage-irrigated tracts were nearly identical to those watered purely with low-salinity canal water.

Rawlins left the salinity lab in 1980, moving eventually to an administrative job in the Agricultural Research Service's national office. But Rhoades worked with more junior scientists to continue the drainage reuse studies in the Imperial Valley starting in 1982. Again funded by the Department of Water Resources, Rhoades this time designed an elaborate trial involving two cropping rotations—wheat, sugar beets, and cantaloupes in one plot and cotton, wheat, and alfalfa in the other. Both ran for four years in the Imperial Valley's twelve-month growing season, producing two full rotations of each crop in the first case and two cotton crops, one wheat crop, and two full years of alfalfa harvests in the second rotation. There were two water sources: water with relatively low salinity from the Colorado River, and water from a local stream, the Alamo River, which consisted mostly of drainage from Imperial Valley farms. The Alamo water was about three times as salty as the Colorado water. Rhoades used the fresher Colorado water to establish seedlings on all rotations, but for subsequent irrigations, he substituted salty Alamo water for one-half to two-thirds of the crops' water needs. He planned the rotations to include both salt-tolerant crops like cotton and more sensitive crops like alfalfa and melons, and he set up his irrigation schedules so that, after a period of watering a salt-tolerant crop with Alamo water, he then watered a sensitive crop with Colorado water. Although soil salinity levels rose when the Alamo water was used, they dropped when the Colorado water was substituted; in the end, the soil salinity was roughly what it was in the beginning, and there was no reason why the entire cycle couldn't be repeated over and over in perpetuity. For all the crops and all of the combinations of Colorado and Alamo River water, the results were essentially the same as in Lost Hills: yields were no different from those produced by a steady diet of low-salinity water.

The results of these two experiments supplied a way to circumvent the dilemma identified by Rawlins—that no matter how efficient their irrigation methods, farmers would never be able to reach the theoretical minimum leaching fractions that could be produced in the lab's lysimeters. Reusing drainage to irrigate crops in carefully planned rotations and in alternation with fresher water supplies, Rhoades showed, could give farmers two chances to concentrate their drainage instead of just one. Each reuse reduced the volume of the drainage water a little bit further, as part of the water evaporated and part was used by the crop. In the end, Rhoades estimated that total drainage volumes could be reduced by 80 percent through a combination of minimized leaching and drainage reuse. Though the remainder still required disposal, reducing the total quantity of the drainage would make that disposal both easier and more economical, just as it had in the Wellton-Mohawk Valley's minimized leaching trials. Carried to its logical conclusion, the process could reduce drainage volumes to a mere trickle by adding a final rotation of extremely salt-tolerant plants such as eucalyptus or *Atriplex*.

And yet, on a gray winter afternoon more than five years after the Imperial Valley experiments had concluded, Rhoades sat in his office at the salinity laboratory and lamented the lack of acceptance his methods had found among desert farmers. Rhoades by that time was the lab's director. Age had softened some of the rough competitive edges that had led to his earlier battles with the other scientists, and former rivals now applauded his newfound colleagueship and leadership skill. "I couldn't be happier with what I see happening at the salinity lab right now," Rawlins said. "I think that it's never been in better shape than it is right now, and I give a lot of credit to Jim Rhoades." The lab's minimized leaching and drainage reuse concepts also began to win much wider acceptance, at least among water planners. In 1990, when five agencies including the Bureau of Reclamation and the Department of Water Resources completed a five-year, fifty-million-dollar study of the San Joaquin Valley's chronic drainage problems, they gave a vigorous endorsement of minimized leaching and drainage reuse as a key feature of their proposed cure.

Nevertheless, acceptance from desert farmers has been slow to come. For the most part, the farmers still see salt as the enemy, see salt balance as a necessity, and believe with all their hearts in a 30 percent leaching fraction. "They don't want to use saline water voluntarily," Rhoades said. "They all believe that it can only lead to trouble for them, so they want to avoid it." But he remains philosophical about the lack of progress. When farmers finally run out of places to dump their saline drainage, he reasons, then they will be ready to listen to him and change their practices. When that happens, Rhoades and the other salinity lab scientists will have the techniques the farmers need, ready and waiting for them. Rhoades said:

> No farmers are going to voluntarily do this, and I never believed that, even in the very beginning when I started this work. I never felt that farmers are going to jump on the bandwagon and go rushing up and down the road congratulating me, because they all come from a different viewpoint: "Just give us more good-quality water. That's the solution." But when push comes to shove and they've finally got to start to do some things, then at least they're going to have some evidence and some understanding to base it on.

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CHAPTER ELEVEN

A Vision for the Future

Buried somewhere in the archives of the U.S. Patent Office is an 1874 document describing the first device ever invented for drip irrigation. It was a model of simplicity, consisting of an iron pipe drilled with nearly microscopic holes to let trickles of water dribble from its slightly pressurized innards—an ingenious device, but one that was fatally flawed. For one thing, it cost too much. To irrigate a fair-sized orchard would have required many miles of pipe and a correspondingly enormous outlay of capital. Besides, it didn't work. The tiny holes clogged almost instantly; corrosion and bacteria sealed them tight in a few days if a sand grain didn't do the job first. Nor surprisingly, the device never went into commercial production.

In the decades that followed, other inventors tried to perfect similar devices. In the 1930s in the Goulburn Valley of southeastern Australia, growers punched holes in galvanized pipe to water their fruit trees, but their efforts fared no better. Throughout the first half of the twentieth century, eager inventors experimented with various iterations of perforated pipe, but none succeeded—not until 1959, when the development of cheap, durable plastics allowed the invention of a workable drip irrigation device by three men from the new and intensely arid nation of Israel. A resourceful

retired tinkerer and a pair of younger, ambitious agricultural scientists, they showed the world how the ancient Sumerian art of irrigation could be reborn in the age of high technology.

The life story of Simha Blass has become a legend in the world of irrigation technology, and like most legends, it now consists of about equal portions fact and fantasy. The basic story goes something like this: in the late 1950s, Blass had just retired from Tahal, the Israeli government's water resources agency, and was working with his son to develop new irrigation technologies. One day, he was transfixed by a slowly leaking sprinkler head and the green and vigorous grass that surrounded it. Watching droplets of water gradually swell before breaking loose and striking the ground, Blass began to ponder drip irrigation and its problems, which by then must have seemed insurmountable: the clogging; the cost; the challenge of ensuring that each outlet emitted the same amount of water despite pressure variations within the pipelines.

Soon Blass set to work in his garage, experimenting with different designs and materials. When he emerged weeks later, he had developed a new plastic dripper whose design was distinctly different from the failed earlier models. Whereas the others had consisted simply of holes drilled into pieces of pipe, Blass's new device added a serpentine internal passage that the water had to zigzag its way through before reaching the outlet. Forcing the water to take such a tortuous route accomplished two things. First, it created turbulence, which helped to keep sediment in suspension and reduced the buildup of algae and bacteria. Equally important, the complex switchbacks sharply reduced the pressure of the water as it passed through them. This meant that Blass could use high pressure to even out the natural pressure variations while maintaining a slow rate of drippage. It also meant that he could make the drip orifices themselves considerably larger than those on earlier drippers, which helped to reduce clogging. Blass's new device with its zigzagging drippers enabled irrigators to lace their fields with high-pressure water lines leading directly to each individual drip outlet;

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then, with no moving parts, the drippers magically transformed the high-pressure water into a lazy dribble. The device was reliable and cheap, and it seemed to have strong market potential. Soon Blass had licensed its manufacture to Kibbutz Hatzerim, a small collective farm that was looking to diversify into manufacturing; thus was born Netafim, one of the world's largest producers of drip irrigation gear.

But success did not come as quickly as Blass and his partners might have expected. In initial trials in southern Israel's Negev Desert, the new drippers failed miserably. Early experimenters, hoping to use the devices to reduce evaporation to its absolute minimum, buried the drip lines in the ground, where they quickly became clogged with sediment and root growth. Digging up the lines for repairs was hugely expensive, and for a while the promise of the new technology seemed like another cruel hoax. But then in 1964, the Hebrew University opened a research station in the broiling Arava Valley of extreme southern Israel—a below-sea-level oven lying between the Dead Sea and the Red Sea. The Arava is the lowest point on earth not covered by water; a permanent low-altitude haze smothers the valley like hot fog. At the time, there was not a hint of green on its saline brown and gray soils, and there was no good water to speak of. Yet Israel, worried that its unpopulated frontier was vulnerable to then-hostile neighbors like Jordan and Egypt, was determined to promote agricultural settlement in that bleak desert basin. The station's assignment was to find a way to make that possible.

To staff its new research post, the university sent S. Dan Goldberg, a Jerusalem-born irrigation lecturer, and Menachem Shmueli, one of Goldberg's recent graduate students and an immigrant from the prewar Netherlands. During the next two years, Goldberg and Shmueli worked closely with newly established kibbutzim to create fertile farmlands from the harsh Arava plains. They sowed winter vegetables for European markets and installed elaborate drip systems, this time with the lines running over the

ground instead of below it. In time, they not only proved that it was in fact possible to grow crops in the Arava with drip irrigation but also showed that simply by mixing fertilizer with the irrigation water, they could produce yields twice as large as by conventional farming methods. "The results that we received were outstanding," Goldberg said in a 1990 interview, "I have pictures, slides, where you can't see me for the tomatoes."

Goldberg and Shmueli's work in the Arava resulted in a 1970 article in *Transactions of the American Society of Agriculture Engineers*—a paper that sparked interest around the world in the new technology. Four years later, there were two world congresses on drip irrigation, and by 1982, an estimated one million acres worldwide were on drip systems. In later years, the Israelis exported their innovation everywhere, even to their erstwhile enemies: by 1990, only one nation outpaced Israel in the proportion of its farmland watered with drip, and that was its neighbor, Jordan. Meanwhile, scientists at such institutions as the Hebrew University, the Volcani Institute, and Ben-Gurion University of the Negev used drip irrigation to reassess old notions of what constituted usable water. In the Arava, Goldberg and Shmueli had tapped into brackish aquifers to irrigate their crops; they found that by using drippers to keep a constant flow of water through the root zone, they could prevent the spikes in soil-water salinity that resulted from the wetting-and-drying cycles of traditional irrigation. That, in turn, made it possible to use water of higher salinity for irrigation: as long as there was no further increase in salt concentrations as the water moved through the soil, the plants were in no osmotic danger. In succeeding years, one Negev kibbutz not far from Sde Boker successfully grew sweet corn—a notoriously salt-sensitive crop—with brackish groundwater that had a salinity content of about three thousand parts per million, about three times as salty as the Colorado River at the United States–Mexico border. Other scientists focused on breeding plants that could tolerate still higher levels of salinity. At the Ben-Gurion campus in Beersheba, Samuel

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Mendlinger, a New York–born plant biologist, came up with a melon that tastes like a canteloupe, matures early enough for lucrative export markets, and thrives on water with salinity at four thousand parts per million. At the Sde Boker campus, Jiftah Ben-Asher tinkered with nutrient levels for drip-watered plants and proved that the simple expedient of adding fertilizer can help many plants adapt to water of higher salinity.

Behind all of these projects lay a peculiarly Israeli combination of meteorological realism and Zionist ideology. An emphatically dry nation, especially in its southern half where most of its arable land lies, Israel from its birth in 1948 has searched, struggled, and sometimes fought for water. Water has always been an important—though often unrecognized—factor in the conflicts between Israel and its neighbors. When in 1965, two years before the historic Six-Day War, Syria began constructing diversion works on a Jordan River tributary called the Banias, Israel attacked, stopping construction and raising tensions. In the subsequent war, Israel seized not just the nearby Golan Heights, from which ramparts Syrian soldiers had been firing on the kibbutzim below, but also the lower-lying headwaters of the Banias, which posed no military threat. Israel also has clashed with both Syria and Jordan over those nations' claims to the Yarmuk River, another Jordan tributary that joins the main stream a few miles below Yam Kinneret, the biblical Sea of Galilee. And critics have suggested that Israel overran the highlands of southern Lebanon in 1982 partly in order to divert the Litani River, which drains the Bekaa Valley before emptying into the Mediterranean just north of the Lebanese-Israeli border.

This lust for water was driven principally by a severe shortage of it at home. Israel's water resources, always few and fragile, are concentrated in the rugged Galilee region of the country's north. To move water from there to the dry but arable south, the nation began shortly after independence to construct a 108-inch pipeline called the National Water Carrier. Finished in 1964, the pipeline

traverses the forty-eight miles from Yam Kinneret to Tel Aviv, picking up small amounts of spring and well water along the way to mix with an initial infusion of water pumped from the lake where Saint Peter fished. At Tel Aviv, the pipeline splits into two branches and continues another sixty miles to the northern Negev, an arid, mostly barren extension of the Sahara that occupies more than half of the nation's territory. That precious water, pumped uphill more than six hundred feet from the Kinneret and across more than a hundred miles of terrain, now supplies virtually every farm, home, and business within the pre-1967 borders of Israel. But this water is not nearly enough for a nation that, despite its aridity, yearns to be agricultural.

From the start, agriculture has been deeply engrained in the Zionist ideology that defines modern Israel. It is considered a key to the nation's military security—settled land being far easier to defend than empty land—and its economic survival, and it is pursued with a single-mindedness of purpose that borders on the messianic. The nation's first prime minister, David Ben-Gurion, exhorted his compatriots to "bloom the desolate land, and convert the spacious Negev into a source of force and power, a blessing to the state of Israel." In retirement, Ben-Gurion kept faith with his words and made his home on a Negev frontier kibbutz abutting the desolate Sde Boker campus of the university that bears his name.

"The Zionist ideology fostered a return to the land," explained Moshe Brawer, a Tel Aviv University geographer. In biblical times, when the Jews last had their own state, the principal occupation of most had been agriculture; its revival would link the new Israel with its ancient predecessor in a palpable way. But that was not the only factor; pragmatic issues of security were at least as important. With waves of immigrants arriving, Israel had severe food shortages, and surrounded as it was by hostile neighbors, self-sufficiency seemed to be an imperative. In addition, the new nation's grip on its sliver of real estate was so tenuous that land settlement was considered

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necessary for national defense, just as it had been on the U.S. frontier a century earlier. Finally, agriculture filled another critical need, Brawer said: "There weren't many job openings to occupy the many immigrants who came, and agriculture was one of the main possibilities for employment."

The fact that few of those immigrants had previously worked in farming actually made the transition easier, Israeli experts say. The nation quickly developed an efficient extension service, set up collectivist kibbutzim and moshavim, and began educating newly employed workers in the latest agricultural techniques. The instructors found their students eager to learn. "When we look back and try to understand why agriculture in Israel developed so quickly, and to such a high level, probably one of the reasons was that these people knew nothing about agriculture," said Yona Kahana, general director of the Israel Institute for Waterworks Appliances, which develops and promotes technologies like drip irrigation. The neophytes were blank slates, Kahana said: "They would listen to the instructor, and they were open to what they were told, whereas most established farmers have their own traditions, beliefs, and prejudices." For the same reasons, Israeli irrigation systems have always tended to be technologically advanced—sprinklers in the early years, with drip making inroads beginning in the late 1960s; systems like those cost more but were far easier for the beginners to run than the traditional ditches, siphons, and furrows of surface irrigation. "All they had to know was when to open the valve and when to close it, and where to go if something went wrong," Kahana said. "They learned by doing. We actually invested much more per unit, but our farms produced almost immediately."

Israel's experience shows what can happen when a society starts with a clean slate and builds an agricultural infrastructure using only the best, latest, and most sensible equipment and techniques. By taking advantage of drip irrigation's ability to calibrate a crop's water and fertilizer rations with great precision, the Israelis have

produced harvests that outdo those produced by traditional methods. Well-managed drip systems, the Israeli experience shows, can more than pay for themselves through increased yields, especially when water is priced at market value, as it is in that country. But why, then, haven't drip irrigation and other high-tech systems made a dent among tradition-bound desert farmers elsewhere, not even in places like the United States, which could easily absorb the systems' admittedly high capital costs? The reasons may be rooted in fear—the fear of taking a risk, of deviating from past practice, of learning something new.

In the fall of 1990, Jack Stone, the crusty and outspoken septuagenarian chairman of the Westlands Water District, sat in his ranch office on a blustery morning and talked about his objections to the new technology, which had been the subject of a recent experiment by scientists from the University of California Cooperative Extension Service and the Agricultural Research Service, who installed drip lines under ten acres of cotton on Stone's eighty-six-hundred-acre ranch. "I'd be delighted if somebody would come up with a drip system that would be practical for me or anybody else to use," Stone said. "Up to this point, for field crops, I haven't seen such a system." Stone admitted that drip systems could be useful for tree and vine crops—in fact, he had just finished installing one in an almond orchard—and that fact set him apart from many of his peers in the San Joaquin Valley. "I think it's a tremendous success," he said, "although I don't think it saves much water. But it uses water efficiently so you don't have any tailwater, and you get a good crop."

Stone was less sanguine about drip's prospects for cotton, tomatoes, and garlic, the mother lodes of the western San Joaquin Valley's agricultural bounty.

> The only other experience I've had with drip was that subsurface drip on that ten acres, and that has been quite a problem for us. There's the problem of keeping the lines repaired if they break for some reason or another. There's the problem of keeping them clean—no way in the world can you clean them if they get plugged up. And there's the prob-

lem of the growth that gets in there, bacteria and so on. We have to flush that out with chemicals. All of that is very technical work. We've got ten acres, and the folks that work with that have to watch it like a hawk. If I had a large acreage of that, I'd certainly have to have a good man on it. It couldn't be just any regular irrigator. He'd have to be some kind of a technician.

As a result, even though he farms in an area that has severe drainage problems and chronic water shortages, and thus would seem ideal for drip's water-saving capabilities, Stone said he would rather continue to irrigate by gravity, just like the ancient Sumerians. Drip "looks real good, but this old ditch and a truckload of siphon pipes and a good irrigator," he laughed, "boy, that works great."

Claude Phene, research leader at the Agricultural Research Service lab in Fresno and a designer of the subsurface drip project at Stone's ranch near Lemoore, scoffs at such comments. Phene spent most of the 1980s looking for solutions to the flaws that torpedoed Israel's early subsurface drip experiments and succeeded in almost every respect. He found several ways to prevent roots from clogging the emitters; his favorite was regular injections of phosphoric acid, which deterred root growth while also giving crops needed nutrients. Chlorine controlled algal growth, and improved filtration helped keep sediment out of the system. By 1990, Phene's lab was testing subsurface drip on farms throughout the San Joaquin Valley, and it found, just as the Israelis did, that drip systems not only saved water but raised yields dramatically. "Drip irrigation requires a more intensive level of management, but it also gives you more manageability than a furrow system," Phene said. Not the least of its advantages has nothing to do with water: drip also enables farmers to deliver nutrients to their crops in the exact quantities required for each stage of growth. While conventional farmers might have to send tractors into their fields to apply extra fertilizer in midseason—assuming they don't just apply an extra heavy dose at planting—drip farmers can simply spike their systems with nutrients when needed, delivering them automatically.

That not only saves money by reducing fertilizer waste, it also ensures that plants won't be undernourished either, which helps to boost yields toward their theoretical maximums.

But where drip irrigation truly shines is in its ability to micromanage the flow of water. Phene is convinced that drip irrigation is the best way for San Joaquin Valley farmers to battle their twin menaces of poor drainage and meager water supplies:

There's a reason for the drainage problems they're having now: they've over-irrigated for many years. Now, the water table is high and it has no place to go. And you've got two ways to address it. You can either treat the source of the problem or you can treat the results. Personally, I think you have to look at both; you have to look at applying less water, more uniformly, and you have to look at disposing of some of the drainage water, because you cannot operate irrigated agriculture in a semiarid climate without drainage.

Drip can help to apply water sparingly and uniformly because of its precision, Phene said. It allows farmers to control water use down to the millimeter, which in turn allows them to reduce leaching to the absolute minimum required by the crop, soil, and water they have. "The quality of water that's coming down the California Aqueduct is excellent; all you need to leach is about 2 to 3 percent per year," he said. "Unfortunately, you cannot do that with furrow irrigation. With drip irrigation, on the other hand, you can do it." Such minimized leaching can drastically reduce the amount of drainage produced, and that may prove to be the key to making agriculture sustainable in the San Joaquin Valley. If dumping the valley's saline drainage into the Sacramento–San Joaquin delta is out of the question, as it appears to be, then farmers will have to consider more expensive options—desalting, evaporation ponds with nets to prevent bird use, or pipelines to the deep ocean, for example. Such options are obviously too expensive as long as drainage flows are in the hundreds of thousands of acre-feet per year. But if those flows could be reduced to, say, tens of thousands of acre-feet, then the alternatives may be viable.

Some valley farmers are taking Phene's work seriously. John

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Harris, son of Westlands pioneer Jack Harris and a major power in the valley's agricultural establishment, is gradually converting his seventeen thousand acres of tomatoes, cotton, and vegetables to a subsurface drip system using a lightweight plastic drip "tape" buried eight inches below the surface. The tape is cheaper than heavier drip hoses, and because it's buried shallower, it's less expensive to install. On tomatoes, the system uses 40 percent less water and produces more and bigger fruit, with less rot because the tomatoes don't rest on moist soil. Not far away from Harris, another grower converted 750 acres of raisin grapes to subsurface drip and cut his water use in half. His vines are now healthier too, Phene said, because unlike surface irrigators he can continue watering them during the three-week period in late summer when growers lay paper trays of grapes on the vineyard floor for drying.

Still, most valley farmers remain wedded to the tried-and-true methods of gravity-powered irrigation, Phene said. "There is some conversion to drip irrigation, but by and large it's relatively small scale. California has close to ten million acres of irrigated agriculture and maybe one-half to three-quarters of a million acres is drip-irrigated. And the drip-irrigated acreage is mostly on trees and vines and high-priced crops like strawberries and some vegetables." Besides the up-front capital costs, Phene said, the main obstacle to greater acceptance of drip is ignorance:

> Most of the farmers, they don't know anything about it. The young guys have a tendency to go easier; it's easier for them to see the difference. But the guys who have been around for twenty or thirty years, they don't want to change. They are used to doing things one way, and they've been successful, so they figure why should they change? And they won't change until somebody pushes them enough to do it.

What ends up pushing the farmers, and the society they feed, may be simple survival. Suppose for a moment that the progress of human civilization had stopped at the hunter-gatherer stage. Suppose that the Nile tribes had never sowed seeds behind the river's annual floods; that animals had never been put to work in the fields; that the British had never diverted the Indus rivers to faraway deserts; that the Colorado River still ran red to the Sea of Cortez; that the miracle dwarf grains of the Green Revolution had never been developed, nor the chemical fertilizers and pesticides and irrigation systems required to support them. Suppose all this were true, and then imagine how sparse the world's population would have to be. At the birth of the Nile, Indus, and Mesopotamian civilizations, the entire planet held fewer than 100 million people, maybe far fewer. In the mid-nineteenth century, at the dawn of modern irrigated agriculture, it had about 1.3 billion. By the 1950s, when Asian famines prompted the research that led to the Green Revolution, there were just under 3 billion. Now, at the end of the twentieth century, with high-yielding seeds and modern, massive irrigation in use on every continent except Antarctica, the world has more than 5.3 billion people.

Yet except when food supply lines are disrupted by wars and other disasters, almost all of the world's current multitudes are fed at least enough to subsist. The proportion of people who go to bed hungry has actually declined in the past forty years, from 23 percent in the early 1950s to 9 percent in the mid-1990s. Without irrigation, this almost certainly would not be the case. Take away the extra increment of yields attributable to the use of imported water, and the food surplus that enables the world to carry its current population would quickly vanish. In this light, two disconcerting trends are worth nothing: world population continues to spiral upward, with current estimates now projecting 8.6 billion people by 2025, less than half a lifetime from now. Meanwhile, the productivity of the planet's hard-won irrigated acres, now responsible for one-third of the world's food supplies, is stagnant or in decline, with some 150 million acres—25 percent of what was brought into production over a century of feverish dam and canal construction and water diversion—now affected by salinization, waterlogging, or both.

Some experts foresee a Malthusian crisis in decades to come.

"Soil erosion, air pollution, soil compaction, aquifer depletion, the loss of soil organic matter, and the waterlogging and salting of irrigated land are all slowing the rise in food output," writes Lester R. Brown, president of the Worldwatch Institute. "At present there is nothing in sight to reverse the worldwide decline in grain output per person. The bottom line is that the world's farmers can no longer be counted on to feed the projected additions to our numbers." Malthus, of course, was wrong in his predictions of an eighteenth-century global population crash, and these latter-day experts may be proven wrong as well. But Malthus erred mainly in failing to foresee how industrialization could stretch scarce resources to accommodate a burgeoning global population. Whether agriculture in the twenty-first century will be able to perform a similar magic act—building on the technological advances of the last century and a half without losing ground to side effects like salinity—remains an open question.

Still, there is good reason to be hopeful. At present, agriculture worldwide is not even close to making full use of the technological innovations that have brought it to this point. The recent history of agriculture is characterized by a steady rise in average yields brought about through increasingly more efficient management of the inputs of production. Today, the popular image of the farmer as a barely educated bumpkin is laughably out of date, at least in the developed world. Farming these days requires degrees in agronomy, familiarity with personal computers, and a good working knowledge of chemistry, botany, and economics. Producing crops is now much like producing manufactured goods. The manager of a large farm today has more in common with a General Motors factory superintendent than with a backyard gardener. Instead of steel, rubber, and fabric, the farm's inputs are sunlight, nutrients, water, and germplasm; its machinery is the soil; and nature does much of its labor. But the process is strikingly similar. And just as the automakers have increased productivity by investing in new factories and new materials, so has agriculture

increased per-acre yields by tinkering with its inputs. At first, farmers saved seeds from their best plants and set them aside for the next year's crop. Later, plant breeders began crossing strains with desirable traits to produce superplants, like the dwarf wheat and rice of the Green Revolution. Now, scientists are using the polymerase chain reaction and other genetic engineering tools to tinker with the DNA of plant cells to produce still stronger and more fruitful crops. Chemical fertilizers supplanted manures after World War II; today's high-tech organic farmers are nourishing their soil by planting leguminous cover crops in their orchards and vineyards and planning complex crop rotations that include nitrogen fixers. Water management made its first great leap forward when the British diverted the Indus rivers; then, during the twentieth century, it made another with the introduction of plastic siphon tubes and laser-guided land levelers, devices no Sumerian could have dreamed of.

Now it is time for another great leap. Drip irrigation, or something like it that is similarly stingy with water and allows farmers to micromanage their crops' water and nutrient rations, would complete the technological revolution that the British engineers began a century and a half ago, just as genetic engineering has the potential to complete what Gregor Mendel began with his pea plants in the monastery. When the British diverted the Indus rivers they transformed the ancient Sumerian art and gave the world the ability to feed its teeming populations of the twentieth century, but the transformation was left unfinished. In the Indus, where illiterate peasants today struggle with one of the world's most technologically complex irrigation networks, the introduction of Green Revolution wheat seeds by itself boosted yields by 60 percent in two years in the late 1960s. But yields there and in other developing nations from Mexico to Morocco still fall short of what they should be, mainly because farmers lack the training necessary to manage their fields to the demanding standards of the last decade of the twentieth century. Meanwhile, in developed nations like the

United States, even well-educated farmers cling to outmoded methods because they won't accept the risk that accompanies change. A 1982 study by the United Nations' Food and Agriculture Organization estimated that there is enough farmland, sunshine, and water on the planet to support not five or ten billion but thirty billion people—but only if all of that land is managed to maximize yields with technologies that are now in use. A world with thirty billion people may be frightening to contemplate, but a world with ten billion is probably a certainty within the lifetimes of today's children. Highly efficient irrigation systems, and the concomitant increases in the efficiency with which nutrients are delivered to plants, may be all that will permit agriculture to make a graceful transition into the twenty-first century, when it will have to feed twice as many people as today.

Considering the evidence to date, the transition is not at all certain to be made. The environmental side effects of modern irrigation are creating problems all over the world in places like the Kesterson National Wildlife Refuge, the Tulare basin, the Colorado River delta, the Aral Sea, the Riverine Plain, and the valleys of the Nile, Indus, and Tigris-Euphrates. In some places, as in Pakistan, the damage is already severe; in others, such as the San Joaquin Valley, the reckoning may be still a few years or decades away. But there is not much time. An expert study completed in 1990 predicted that 460,000 acres of the valley's irrigated farmland may go out of production because of drainage problems by 2040, at a cost of nine thousand jobs and $441 million in crops. Meanwhile, production on irrigated land worldwide is stagnant on average and declining in many places. And even aside from any loss of production, as world populations continue to double and redouble they may soon outstrip the gains won by decades of improved plant breeding, nutrients, and irrigation. No one knows for certain when the two curves of population and food production will meet, or where the first effects will be felt. All that can be said safely is

that it is still uncertain whether this civilization of ours, on the cusp of its third millennium, will continue to prosper or collapse like its predecessors.

The climate of the valley of the Tigris and Euphrates rivers has changed little over the millennia. It is a desert today, and it was a desert at the dawn of Sumerian civilization forty-two hundred years before Christ. At least eleven empires have risen and fallen in that arid valley, but today modern Iraqis are able to produce only a little salt-tolerant barley there, even after spending vast sums of money to reclaim the salt-poisoned soil. Five thousand years ago, in contrast, the ancient Sumerians grew bountiful crops of wheat on those same lands. Their surpluses enabled them to expand their city-states from their bases in the southern end of the valley; they built fortifications, raised armies, and attacked their neighbors, just as modern civilizations are prone to do. They prospered for at least a thousand years. But today, the southern Mesopotamian plain is a lightly populated and impoverished region, insignificant in comparison with the more prosperous central and northern parts of Iraq.

What happened? What could explain the slow but calamitous decline of the world's most highly developed civilization—a society that achieved literacy three millennia before Christ? Some clues were provided by a group of anthropologists from the Oriental Institute at the University of Chicago, who deciphered cuneiforms and other records and found evidence of an ancient dispute over water that turned disastrous. Two Sumerian city-states shared a watercourse that struck out from the Euphrates into the desert. About 2400 B.C., the upstream city, Umma, decided to cut off some of the flow to its downstream neighbor and keep more of the water for itself. The downstream city, Girsu, responded by building a canal in the opposite direction that linked with the Tigris. The new canal was safe from Umma's larceny, and with its water supply secure, Girsu continued to thrive. Over the succeeding years, it gradually enlarged the Tigris canal. New lands were irrigated, and more water was made available to the surrounding plains. But with so much water at their disposal, Girsu's farmers became profligate in their water use. They over-irrigated, and with nowhere else to go, the excess water merely seeped down to the water table. Slowly, the water table rose. The groundwater, which may have been only slightly salty at the time, was wicked up toward the surface as if through a sponge. After several centuries, so much salt built up in the soil that wheat would no longer germinate.

The anthropologists counted the impressions left in pieces of carbon-dated pottery by the different types of grain and found that wheat farming had been almost completely replaced by barley in the lower Mesopotamian plain by 1700 B.C.; two thousand years earlier, the region's production had been equally divided between the two grains. Eventually, the soil grew so salty that even barley refused to germinate. When that happened, ancient Sumeria went into eclipse, and the locus of Mesopotamian civilization quickly shifted upstream toward what became Babylon. What had started as a great civilization based on a successful irrigation system ultimately was transformed, by virtue of over-irrigation, into a salt-poisoned wasteland.

At more than 3000 years, the longevity of the ancient Sumerian civilization exceeds that of any other civilization to this day. In contrast, what we have built in the world's arid regions in modern times is still in its infancy. It has been only 150 years since the British overran the valley of the Indus; less than a century since the Bureau of Reclamation was founded; not even five decades since the Central Valley Project was built. Without a sustained effort to head off the disastrous side effects of that project and others like it, future archaeologists may be left to puzzle over what became of us as well.

Bibliography

Because the predominant source for this book is the author's decade of reporting on desert agriculture in California and elsewhere, this bibliography is not intended to be exhaustive but rather a summary of major published and documentary sources for each chapter. Those who want to read more on desert agriculture and water should start with such books as Tom Harris's *Death in the Marsh* (Washington, D.C.: Island Press, 1991); Marc Reisner's *Cadillac Desert* (New York: Viking, 1986) and *Overtapped Oasis* (Island Press, 1990); Philip Fradkin's *A River No More* (Tucson: University of Arizona Press, 1984) and other titles by the same author; Donald Worster's *Rivers of Empire* (New York: Pantheon, 1985); and Norris Hundley's *Water and the West, Dividing the Waters,* and *The Great Thirst* (all from University of California Press). John McPhee's *Rising from the Plains* (New York: Farrar, Straus & Giroux, 1986) is an excellent read on selenium and its geology. The Worldwatch Institute's annual *State of the World* (New York: Norton) reports and its other publications do an outstanding job of illuminating the otherwise neglected threat of stagnant or declining agricultural yields in the face of steadily rising populations.

Chapters 1, 2, and 3

The literature of irrigation and the development of the U.S. West is a treasure trove; the titles below represent a mere sampling. The Bureau of Reclamation publications listed are the best resources for learning about the broad sweep of the bureau's works in the seventeen states that it serves. In addition to the sources listed below, many of those listed under chapters 6, 7, 8, 10, and 11 were also used in preparing these chapters.